ABSTRACT: Even if recent effort in developing methodology and measures for design structures against fire and explosions has been mostly focused on buildings, bridges can also be very sensitive to those actions, as witnesses by some recent bridge accidents, which caused major economic losses and also endangered people safety in few cases. Purpose of this paper is making a focus on the state of the art of the research and current regulations concerning the response of bridges to fire. Several cases of bridge fires are reported and a focus is made on the occurrence and consequence of bridge fires, considering both the costs deriving by structural damages and by limited serviceability and other indirect societal aspects. Few cases of recent bridge fire are reviewed in detail and structural consequences are highlighted, distinguishing between damages directly induced by fire and damages induced by local failures.

1 INTRODUCTION

1.1 Accidental situations for structural design

Nowadays a general consensus seems to be achieved among the civil engineering community on the need of taking into account in the design the behavior of structures to exceptional events, such as impacts, fire and explosions (GSA, 2003; UFC 4-023-03, 2003; Ellingwood, 2006; Giuliani, in press).

However, the design against fire and explosion in particular is mostly limited to the case of buildings and hardly considered in the design of bridges. The reason why most bridge regulations and guidelines, contrarily to building codes (ASCE 7-02, 2002; ISO 2394, 1998; NTC, 2008; EN1991-2:2006), don’t address the problem of fire safety lies probably in two main considerations:

- the likelihood of a fire is considered higher for building premises, where combustible materials in the form of furniture, books and paper generally occupy a significant part of the floor area;
- the uncertainties related to the characterization of the fire action are lower in a compartment fire, where flashover can be assumed and the maximum temperature of the hot gasses and of the fire can be determined from the compartment properties and content.

1.2 Relevance of bridge fire safety

Even if the assertions are reasonable, the lack of a proper fire safety design of bridge structure is arguable with respect to both aspects of occurrence and characterization of a bridge fire.

With respect to the former, it is well known that bridge fires, even if rare, can have severe consequences. Therefore, the risk associated to the event may not be negligible. The reason is that bridge structure may exhibit a particularly high vulnerability to fire, with this term meaning the sensitivity of the structural system to the action (Augusti et al., 2001; Faber, 2006). This sensitivity is a consequence of the slenderness of the composing members, which, in absence of a proper structural fire design, have often a high exposed surface with respect to the member volume and may also develop high eigenstresses induced by the temperature, in case thermal expansion is partially hindered by the system redundancy.

With respect to the latter, uncertainties in the modeling of the actions are present in all low probability / high consequence (LP-HC) events, due to the fact that neither analytical model nor a sufficiently broad database for a statistical characterization of the action is generally available. The same consideration holds for impacts (e.g. collision of a vessel on bridge piers or of an airplane on a high-rise building), as well as malevolent explosions and arsons in buildings. Those events are generally taken into account in the practice of structural design by a pragmatic definition of accidental fire scenarios (Bon-tempsi and Petrini, 2010), where e.g. the most significant locations for the action to strike are identified the basis of engineering experience and the re-
sponse of the structure is investigated under all identified cases.

An exception is represented by compartment fires in building, since analytical model exist for the characterization of the fire (Pettersson et al. 1976, Wickström, 1985). Given the significantly lower uncertainty in the modeling of the fire action for fire compartments and also the higher frequency of occurrence with respect to the above mentioned LP-HC events typically included in the accidental design situation (EN1990:2001; EN 1991-1-7: 2006), it could be appropriate to distinguish this situation from other accidental design situation and possibly require a higher safety level, as similarly done for earthquakes (Giuliani and Budny, in press).

On the other side, arsons as well as other LP-HC fire related event such as a fire after an earthquake or an explosion could be considered among accidental design situations and a lower safety level could be required.

From the point of view of sustainability in fire design (Torero, 2011), it doesn’t seem reasonable to design a structure that fails after a well characterized and relatively frequent event such as a fire in a small compartment, even if the damage is limited to the fire area and a safe evacuation of people is ensured. Maintaining a full serviceability and integrity level instead in case of more severe exceptional events hits the structure could be economically unfeasible and localized damages could be accepted, provided that a global or major collapse is prevented and a safe egress of user from the premises is ensured.

2 CONSEQUENCE AND OCCURRENCE OF BRIDGE FIRES

2.1 Consequences of bridge fires

From what said in the previous section, severe fire can be expected to may easily cause damages in bridge structures, as a consequence of possible slender steel elements and high exposed surface to volume ratio.

Not only the vulnerability of bridges to fire may be high however, but also the consequence of bridge damages can be more severe than for other structures. This assertion is justified by three different considerations, the first one related to structural considerations, the second one to life safety and the third one related to serviceability aspects.

- Bridges are in most cases quite complex structures, because of:
  i. design characteristics (possible presence of long spans, high towers supporting a suspension system, submerged foundations, etc.);
  ii. a nonlinear structural response (material behavior, geometrical effects, boundary condition);
  iii. a strong interaction between the structure and the actions (traffic-structure, wind-structure, soil-structure), which limit the effectiveness of a simplified design of isolated elements and requires the considerations of the system as a whole.

A consequence of the system complexity is that the susceptibility to a local damage, referred to as structural robustness (Starossek, 2009), may also be high and failures can propagate to adjacent elements and potentially lead to a major or global collapse.

Even if no many examples of progressive collapse of bridges are known (two most notably cases are mentioned in Starossek (2009)), still a robust design of bridges has been a concern of design projects (Starossek, 1999) and research studies (Yan and Chang 2006; Wolff and Starossek, 2009) since many years, as well as a recommendation of current bridge guidelines (fib, 2005; PTI, 2007).

- Bridges sustain generally high traffic from cars, bus and in some cases railways. Local damages and even more major structural collapses can therefore endanger the life safety of many users. Even if the evacuation in case of a bridge fire may not be as difficult as in a building, fire alarm and rescue strategies are also not as much developed and very few studies on evacuation for bridge fires are conducted nowadays (Kindler et al., 2012).

- Since bridges represent an important artery in the transportation system of an urban area, the economical consequence of structural failure are not limited to the costs of repairing but involve indirect costs related to the loss of operability of the structure, which can be significant even when the structural damages are limited. Those costs are represented and not limited to social consequences caused by increased traffic and disservice, costs for substitutive transportation sustained by communal or regional administration, loss of income from possible toll revenue, etc. Furthermore, since bridges are typically a key element of transportation network, even a temporary closure may have repercussion far away from the point of the accident and affect the resilience of the whole urban area to the accident.

The aspects listed above are only qualitative considerations on the possible consequences of a bridge fire, which of course depend on the specific case and structure. However they highlight some critical aspects not generally present in buildings, with the aim of underlining the importance of a proper structural fire design in bridges, even if the occurrence of fire in bridges would be deemed less notable than in buildings.
2.2 Occurrence of bridge fires

With respect to the rarity of bridge fire, it has to be noted that, even if it is quite a rare occurrence when compared to strong wind, heavy traffic loads, fatigue and other actions exerting bridge structural system, bridge fires are not so uncommon when compared to other LP-HC actions such as earthquakes or ship collision with bridge piers, which are instead a common concern in current bridge designs (Hauge et al., 2009) and guidelines (AASHTO, 1991).

In this respect McCabe (2008) reports a survey of type and number of failure causes for bridges in USA. According to this data, about the 53% of bridge failures were due to hydraulic causes such as flood, scour etc, about 12% of failures are imputable to collisions, overloading and deterioration occur each in about 9% of cases, while fire, earthquakes and construction problems represent each the 3% of bridge failures. Even if the survey don’t report the clear sources and the entity of the failure is also not specified it’s interesting to note however that fire seems to cause bridge failure more frequently than ice, fatigue in steel structural system, design problems, soil and other natural hazard such as storms, hurricanes and tsunami, each of them having a frequency lower than 1%.

With reference to the type and frequency of bridge failures, Garlock et al. (2012) mention a survey on bridge failures conducted by the New York State Department of Transportation. According to this survey, hydraulic causes are always the main reason of bridge failures, but fire-induced collapses are reported to be three times greater than collapses due to earthquakes. In this respect, it’s interesting to notice that the survey included some seismic state such as California. The survey however didn’t include cases of bridge fires which didn’t lead to a collapse but still had major economic consequences for the reasons above listed.

An extensive list of bridge fire is also reported in Garlock et al. (2012). From 1995 on, 12 cases of bridge fires are reported: one third of cases led to major collapses, another third suffered local damages of the main structure and the last third did not led to significant consequences. In all reported cases except one, the fire was triggered by an accident involving a trucks transporting flammable material such as gasoline or heating oil.

The only exception is represented by the Big Four Bridge, a railroad US bridge that connects Kentucky and Indiana through the Ohio River, where just few years ago an electrical problem in the lightning system triggered a fire. It has to be noted that the same bridge had experienced three other fires previously, two in 1970 and one in 1987, when a quite big fire developed again from an electrical problem of Christmas lights. In all cases however, there was no rail traffic on the bridge, since the railroad had been closed for many years even at the time of the first fire.

There are other few cases of historical US bridges which were damaged or destroyed by fires triggered in most cases by arsonists. Since 1995 the following cases can be added to the previous mentioned list:

- the Gudgeonville Covered Bridge in Erie County, Pennsylvania, and destroyed by arson on November 8, 2008;
- the 160th Street Bridge in Page County, Iowa, a timber bridge built in 1925 and destroyed by fire on 18 June 2008;
- the Old Bridgeton Covered Bridge in Parke County, Indiana, built in 1968 and burnt down on 29 April 2005 by arson;
- the Delta Covered Bridge in Keokuk County, Iowa, built in 1867 and destroyed by arson in 2003;
- the Jeffries Ford Covered Bridge in Parke County, Indiana, built in 1915 and destroyed by arson on 2 April 2002;
- the Cove Creek Bridge in Crawford County, Arkansas, built in 1937 and damaged by fire in 1999.

All above mentioned bridges were either closed or sustaining a very limited traffic at the time of failure. However the economic consequences of their destruction were not mainly related to the operability of the bridges, but to their historical and in some cases touristic interest. Furthermore, being mostly constituted by covered timber structure, which could have easily and relatively economically protected, these cases well represent the disadvantages of a lack of consideration of fire safety requirements of bridge structures.

The cases listed above, as well as a more extensive list of US historic bridge failures is provided by an US online database collecting cases from the ‘50ies and including several other bridges destroyed or damaged by fires (www.bridgehunter.com, last accessed on March, 2012).

One recent major bridge fire and few other additional cases are traceable in the past years and are here listed in inverse chronological order:

- the very recent case of the 60 Freeway fire in Montebello, CA, on 14 December 2011, which led to the demolition of the overpass, as better described in the following section;
- the truck fire under the Stop Thirty Overpass, on 14 June, 2007, reported by TDOT Media Advisory and described by NewsChannel5 (www.tdot.state.tn.us/mediaroom/2007/061407.htm; www.newschannel5.com/story/6653264/ferocious-fire-plagues-norfolk-southern-train; last acc. March 2012);
- the Norfolk Southern train derailment in New Brighton and the subsequent ethanol fire on 20
October 2006, described in a report of the railway company (NTSB/RAR-08/02, 2006);

- the fire on the Queensboro bridge, connecting Queens and Manhattan in New York City, NY, on 18 October 2005, described by the New York Times (Chan, 2005) and which, according to The Sun (http://www.nysun.com/new-york/tarpaulin-fire-engulfs-queensboro-bridge/21683, last acc. March 2012), started probably in a rubbish pile at a construction site on the upper level of the bridge and spread to the scaffolding;

- the fire-induced cable failure in Rio Antirrio bridge, in Greece, on 28 January 2005, reported in a national document following the incident (Koronaïos et al., 2007) and briefly described in the following section.

A review and an extensive collection of bridge fire data seems quite important in the framework of the assessment of fire hazard for bridges, either in terms of occurrence and causes and in term of consequences of bridge fires. It has to be noted that all known cases of bridge fires occurred in US with the only exception of the above mentioned Rio Antirrio bridge in Greece (Koronaïos et al., 2007) and of the Wiehl viaduct in Germany (Eisel et al., 2007), whose cases are presented in the following. It seems unlikely that other European or Asiatic cities never experienced similar cases of bridge fires. The reason of greater documentation available on bridge collapses in US could maybe be imputable to a longer tradition of structural integrity design for buildings and bridges, here intended as response of structural systems to an accidental or critical event (Giuliani, in press).

3 REVIEW OF SOME BRIDGE FIRE CASES

Few examples among the above mentioned cases of bridges damaged by fire are briefly reported in the following, with the aim of highlighting the different response of bridge structural system to fire and distinguish between design aspects that possibly promoted or reduced the vulnerability or the robustness of the bridges structures to fire.

3.1 Montebello freeway 60 overpass, 2011

Just few weeks ago, on 14 December 2011 at 12:10 p.m., a truck transporting 33800 l of gasoline caught fire on the eastbound 60 Freeway under the Paramount Boulevard Bridge, in Montebello, Los Angeles, CA, USA. (Fig. 1).

Due to the intense heat, the driver and a passenger in the truck had to abandon the truck, but managed to escape uninjured as flames began to consume the tanker’s rear trailer. However, the intense fire, which lasted several hours, severely damaged the reinforced concrete structure of the overpass.

In this respect it’s interesting to point out that the overpass reinforced concrete structures are generally considered to resist well the effect of a fire, due to the thermal properties of concrete and the protection offered to the reinforcement. This is often a misconception however, as also witnessed by some recent cases of concrete building collapses as the Windsor Tower in Madrid, Spain, in 2005 (Ikeda and Sekizawa, 2005) and the Architecture Faculty of Delft University, Netherlands, in 2008 (Meacham et al., 2010). Reinforced concrete elements exposed to fire can be subjected failure of the reinforcement anchorage and spalling (Hertz, 2003) and can be at risk of failure many hours after the fire, due to the time required by the heat to penetrate the concrete core.

In the Montebello freeway incident, the concrete deck was reported to have burst from the extreme heat, which was clearly perceived under the bridge log after the fire had been extinguished (L.A. now, 2011). This represents a particularly dangerous situation for firemen and also for observers, which could be induced to approach the structure as soon the fire is over. In this respect, it has to be noted that even current fire design prescription for concrete buildings only require the verification of the elements during the fire, when the steel is the hottest and don’t consider that the verification after the fire, when the reinforcement bars have cooled down but the inner concrete is hot, could in principle be more severe.

In addition to the consideration above, an important consideration on the structural response to fire is that, contrarily to steel, concrete is not regaining the initial stress when cooled down. The temperature that should not be exceeded for a full recovery of an ordinary, not fire proof concrete is relatively low (ca. 300°C). At this temperature micro-cracks develop as a consequence of material dehydration and thermal expansion of the aggregates (Hertz, 2005): at this point the strength loss is permanent, leading to high costs of repairing even in case the structure has survived the fire without any collapse.

This was the case of the Paramount Boulevard Bridge, where tests were carried out on concrete samples, showed a permanent damage of the concrete structure, which had therefore to be demolished.

The demolition was carried out in two different times: the eastbound overpass was demolished the very next morning after the accident and then also the westbound overpass had to be demolished. The demolition was complicated by the fact that telephone lines nestled in asbestos was discovered inside a bridge and the bridge section had to be carefully dismantled in order not to cut the telephone lines nor release toxic asbestos into the air. As a consequence, the 60 Freeway stayed closed much longer than initially expected with significant repercussions on the traffic in the area.
3.2 McArthur Maze Collapse, 2007

The MacArthur Maze is a multilevel freeway interchange bridge near Oakland, CA, serving several major cities in California. The multiple failures of some bridge sections at the interchange (Fig. 2) on 29 April 2007 represent one of the most renewed and studied cases fire-induced collapses of bridges (Noble et al., 2008; Astaneth-Asl et al. 2009).

The fire was triggered by a truck accident that occurred during the early morning hours. The truck was transporting 32600 l of gasoline, when it overturned on the I-80 / I-880 interchange and burst into flames (New York Times, 2007). The fire, which is believed to have reached very high temperatures, heated the overpass above the incident, which served as connector between the I-80 and the I-580.

With respect to the fire action, it’s interesting to notice that the temperature reached by the fire is not yet clear. Bajwa et al. (2011) reports that initial media reports referred about a temperature of 1650°C, which doesn’t seem however a very reliable data, considering that it’s much higher than the temperature obtainable from a localized fire model (Heskestad., 1995) and even higher than the temperature of severe nominal fire such as the hydrocarbon curve (Shipp, 1985) and on the RWS curve generally used for tunnel fires (NFPA 502, 2008).

Also assuming a very severe fire however, the time resistance of the bridge was quite short, considering that a whole section of the overpass collapsed on the interchange beneath just 20 min from the beginning of the fire. A newspaper article reports that Oakland firefighters had arrived on the scene just 7 min before the collapse (Bulwa and Fimrite, 2007).

The cause of the collapse has been imputed to the failure of the connections, overstressed by significant deflection of the road section, whose steel structure had been strongly weakened by the fire. If the vulnerability of the bridge however was high, the collapse of the upper connector was confined to the section between two piers and the lower connector. Not only was the collapse propagation hindered in the horizontal direction, but also the lower connector, even if damaged by the falling section, resisted the impact without collapsing.

The driver was injured by the fire, but no casualties or other injuries were caused by the accident, which luckily occurred during very low traffic hours. Also, the congestion caused by the closure of the route was limited to few days and lower than initially estimated (Hoge and McCormick, 2007) and, thanks to a very fast reconstruction, the time the connectors remained closed were very limited (i.e. 10 days for the lower connector and just 26 days for the collapsed connector). Nevertheless, the economical consequences were very severe, with an overall costs estimated in about $90 million (including repair and rebuilding costs, free public transportation the day after the incident and loss in toll revenue).

3.2.1 Wiehltalbrücke (Wiehl viaduct), 2004

On 26 August 2004, a passenger car skidded on wet asphalt on the Wiehl viaduct near Gummersbach, North Rhine-Westphalia, in Germany. The car crashed into a tanker truck transporting 33’000 l of gas and diesel. Under the impact, the truck crashed through the guardrail and fell 10 meters off the A4 highway below, leading to the explosion of the fuel tank and the death of the driver (Fig. 3).

Following the explosion, a severe fire developed, which is believed to have reached temperatures around 1200°C. Under the high temperatures the
steel deck of the bridge deformed for a length of 60 m but the structure did not collapsed.

A study on the bridge (Eisel et al., 2007) indicates that the cause of the limited vulnerability of the bridge to fire had to be imputed to the relatively low temperature reached by the elements, which are believed to have not been heated more than 500°C. Contrarily to the case of the MacArthur Maze fire, these temperatures seem to be consistent with the temperature obtained by a natural fire model.

Thanks to the limited damages, temporary repairs could be actuated in the weeks after the accident, when 27 additional steel supports where added and 10’000 tons of contaminated ground were excavated. Almost two years later however, the full rehabilitation of the bridge started which included the complete replacement of the whole damaged section and determined the closure of the A4 highway from 28 June to 22 August 2006 and a cost of €7.2 mil (Schwartz, 2006).

3.3 Charilaos Trikoupis (Rio-Antirrio) bridge, 2005

The Rio Antirrio is the world's longest multi-span cable-stayed bridge (2880 m), which crosses the Gulf of Corinth and connects the towns of Rio on the Peloponnese and Antirrio on mainland Greece (Fig. 4).

The bridge, which had been inaugurated on 7 August 2004, almost 6 years after the beginning of its construction, experienced a quite unusual accident 6 months after the opening. On 28 January 2005, one of cable of the pylon closest to the Rio side, caught fire and collapsed, damaging the adjacent cable and crushing onto the deck.

The cause of the fire is not ascertained, but it’s believed that it could have been caused by lightning strike (Koronaioas et al., 2006). Other theories suggest the possibility that the blaze was sparked by wires rubbing together due to high winds or a short circuit in the electrical wires which run along the suspension cables.

Thanks to the intrinsic robustness of the structure, the bridge resisted the failure of one of the 368 cables composing the suspension system and no significant damages developed. The accident had however a direct effect on the serviceability of the bridge, which remained closed for 4 days and was not fully functional until 7 March, with the road traffic limited to one deck only for over a month. The restoration of the bridge was completed about 40 days after the accident.

4 CONCLUSIVE CONSIDERATIONS

From the review of the cases presented above and of other cases mentioned or more extensively described in literature (Astaneh-Asl et al. 2009; Kodur et al., 2010; Garlok et al., 2012), the following considerations can be drawn:

- More than 20 bridge fires have been reported since 1995, which corresponds to a frequency of more than one occurrence per year in the past 17 years.
- The majority of the fires were caused by a fuel tanker truck accident travelling under a viaduct or falling from it.
- In the majority of cases, bridge structures were significantly damaged and high repair costs had to be sustained.
- The majority of the bridges damaged by fires did not collapses and only in few cases in few cases major structural collapse occurred or the bridge had to be demolished.
- Even in the cases where limited structural damages had occurred, high costs deriving from temporary closure of the bridge and disservice to the traffic had to be sustained.

In view of the considerations above, it seems reasonable to contemplate fire safety design aspects for bridges structures. In particular, the consideration of a fire load case in the form a localized hydrocarbon fire appears sensible for viaducts and overpass, which are mostly subjected to tanker truck fires.

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